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MEMORANDUM

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INCONEL AND TYPE 321 STAINLESS STEEL
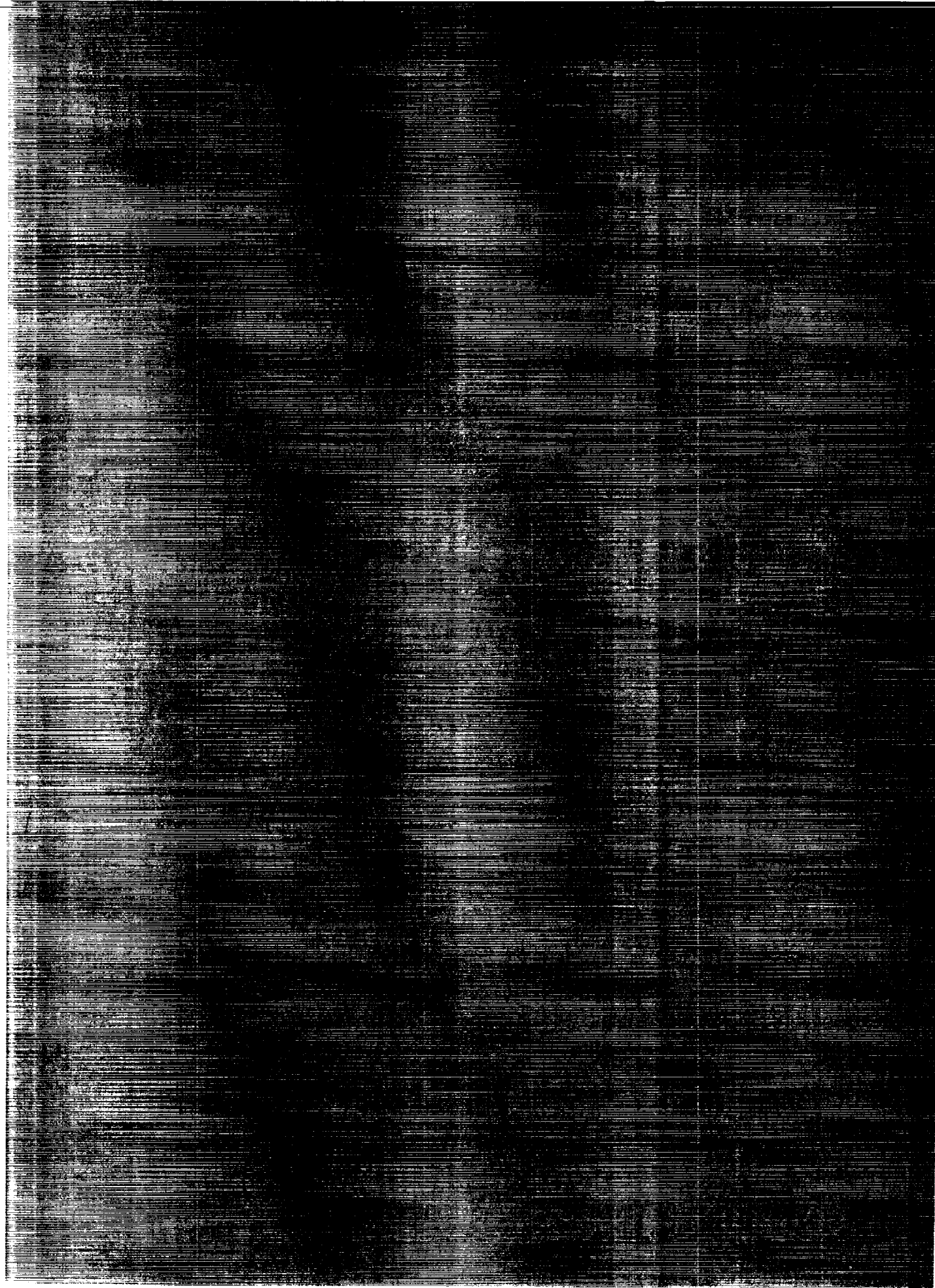
By Joseph C. Richmond and James E. Stewart

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SPECTRAL EMITTANCE OF UNCOATED AND CERAMIC-COATED INCONEL

AND TYPE 321 STAINLESS STEEL

By Joseph C. Richmond and James E. Stewart

SUMMARY

The normal spectral emittance of Inconel and type 321 stainless steel with different surface treatments was measured at temperatures of 900°, 1,200°, 1,500°, and 1,800° F over a wavelength range of 1.5 to 15 microns. The measurements involved comparison of the radiant energy emitted by the heated specimen with that emitted by a comparison standard at the same temperature by means of a recording double-beam infrared spectrophotometer. The silicon carbide comparison standard had previously been calibrated against a laboratory black-body furnace. Surface treatments included electropolishing, sandblasting, electropolishing followed by oxidation in air for 1/2 hour at 1,800° F, sandblasting followed by oxidation in air for 1/2 hour at 1,800° F, application of National Bureau of Standards coating A-418, and application of NBS ceramic coating N-143.

The normal spectral emittance of both alloys in the electropolished condition was low and decreased very slightly with increasing wavelength while in the sandblasted condition it was somewhat higher and did not vary appreciably with wavelength. The oxidation treatment greatly increased the normal spectral emittance of both the electropolished and sandblasted type 321 stainless steel specimens and of the electropolished Inconel specimens and introduced some spectral selectivity into the curves. The oxidation increased the normal spectral emittance of the sandblasted Inconel specimens only moderately.

Of the specimens to which a coating about 0.002 inch thick was applied, those coated with A-418 had higher emittance at all wavelengths than did those coated with N-143, and the coated specimens of Inconel had higher spectral emittance at all wavelengths than did the corresponding specimens of type 321 stainless steel. Both coatings were found to be partially transparent to the emitted energy at this thickness but essentially opaque at a thickness of 0.005 inch. Coated specimens with 0.005 inch or more of coating did not show the effect of the

underlying metal on spectral emittance, and there was no significant difference at wavelengths greater than about 5 microns in the normal spectral emittance of specimens having the two coatings. At shorter wavelengths the normal spectral emittance of specimens coated with A-418 was greater than that of specimens coated with N-143.

In general, the shape of the spectral-emittance curves for specimens coated with A-418 was similar to that for specimens coated with N-143. The normal spectral emittance for the coated specimens increased rapidly with wavelength from 1.5 microns to a maximum at about 9 microns, decreased to a minimum at about 10.5 microns, and then increased to a second maximum at about 13.5 microns.

The normal spectral emittance of all specimens measured tended to increase with temperature at all wavelengths.

INTRODUCTION

Modern aircraft and missiles operating at hypersonic speeds develop high temperatures due to skin friction that may cause undesirable creep and erosion of metallic components. There is also a tendency for such heating to be concentrated at areas of direct impingement, such as the leading edges of wings and the nose cones of missiles. As a result large thermal gradients develop which cause distortion and impair aerodynamic efficiency. In severe cases this distortion may cause total destruction of structural components. Heat-transfer processes in such structures are obviously important because they affect the magnitude of the thermal gradients.

Radiation plays an increasingly important role in heat transfer as the temperature of the hot body increases. In fact, at temperatures above a bright red heat, it will usually account for the major portion of the heat flow between two separated solids. Further, radiation may be the major or sole means of heat loss to the surrounding atmosphere or space. Hence there is an urgent need for information on the properties of aircraft structural materials at elevated temperatures, but data on only a few materials have been published.

Some work has been done in measuring the total emittance of metals and coatings; but, as will be explained in the next section, spectral-emittance values are required for accurate heat-transfer computations. This investigation was undertaken at the National Bureau of Standards, under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics, to supply spectral-emittance curves for two alloys, both when uncoated using different treatments and when coated with two different ceramic coatings, at temperatures of 900°, $1,200^\circ$, $1,500^\circ$, and $1,800^\circ$ F.

DEFINITION OF TERMS

The terminology used in this paper follows the recommendation of Worthing (ref. 1) and is explained as follows:

Emission is the act or process by which radiant energy is emitted by a body as a consequence of its temperature only. This term is also used for the rate of such emission in terms of energy per unit area and time. It is influenced by the composition, thickness, and surface texture of a specimen.

Emittance is the ratio of the emission of the specimen to that of a black body at the same temperature and is influenced by its composition, thickness, and surface texture.

Emissivity is a special case of emittance; that is, it is the emittance of a specimen of material having an optically smooth surface and having sufficient thickness to be opaque.

These terms are modified to indicate the geometric and spectral distribution of the energy accepted for measurement. Hemispherical emission refers to energy emitted in all possible directions from a flat surface. Directional emission refers to the energy emitted at a specified angle to the surface. Normal emission refers to the energy emitted in a direction normal to the surface. Total emission refers to the energy emitted at all wavelengths. Spectral emission refers to energy emitted at specified wavelengths. The spectral emittance or emissivity of a specimen is frequently plotted as a function of wavelength.

FUNDAMENTAL CONSIDERATIONS

The emission or absorption of radiant energy is a complex phenomenon. For an ideal black body that absorbs all radiation incident upon it the amount of radiant energy per unit area emitted at any temperature can be computed from the Stefan-Boltzmann law. This energy will be distributed geometrically in accordance with Lambert's law and spectrally in accordance with the Planck emission law. At any temperature the energy emitted will vary from zero at zero wavelength to a maximum and back to zero at infinite wavelength. At any wavelength the energy emitted increases with temperature, but at shorter wavelengths it increases faster than at longer wavelengths. The wavelength of maximum intensity is inversely proportional to the absolute temperature (Wien's displacement law). Detailed discussion of these laws can be found in most standard physics textbooks.

If these laws applied to all materials, it would be a simple matter to compute the heat transfer by radiation under any given set of conditions. However, while some materials and appropriately formed cavities emit energy in approximate accordance with these laws, the laws apply rigorously only to an ideal black body that does not exist. If a specimen of a material is prepared in appropriate size and surface finish, the departures from these laws represent characteristic properties of the material of which the specimen is composed. Gardom (ref. 2) has discussed in detail the nature of some of these departures.

Absolute measurements of radiant energy are not easy to make. Because the radiation characteristics of a theoretical black body have been precisely defined, it is convenient to evaluate emittance by directly comparing the energy emitted by a heated specimen with that emitted by a comparison standard under the same conditions, then multiplying the observed ratio by the known emittance of the standard (1.0 if a black-body furnace is used).

The amount of energy emitted by a hot body at uniform temperature in free space can be computed exactly by multiplying the energy emitted by a black body under the same conditions, computed from the Stefan-Boltzmann equation, by the total hemispherical emittance of the body in question. The spectral distribution of the energy can be computed exactly by multiplying, wavelength by wavelength, the black-body radiation, computed from the Planck radiation equation, by the hemispherical spectral emittance of the body.

Spectral-emittance values can also be used in computing absorption of radiant energy because for a specimen at thermal equilibrium the emittance is equal to the absorptance (Kirchhoff's law). For opaque specimens the reflectance plus the emittance equals unity. For exact computation of the radiant energy absorbed, the spectral and geometric distribution of the incident energy and the spectral emittance of the body under these geometric conditions must be known.

With few exceptions most materials confirm closely to Lambert's law at angles less than about 55° to 60° to the normal and depart from it markedly only at grazing angles, where the emission of a black body is low. For most materials the normal emittance is higher than the hemispherical emittance by about 5 percent, for which allowance can be made in computations. Hence normal-emittance values can be used in computing heat transfer by radiation with but little error.

A "gray body" emits less energy than does a black body at the same temperature but has the same emittance (fraction of black-body emission) at all wavelengths. Most clean polished metals conform approximately to these conditions. Hence for these materials the spectral emittance at any wavelength is approximately the same as the total emittance.

Ceramic materials and oxidized metals, however, are not gray bodies but show marked variation in spectral emittance with wavelength. Most of the metals used in aircraft structures oxidize appreciably when exposed to high temperatures in air and hence soon lose their gray-body characteristics when heated in an air atmosphere.

Goodman (ref. 3), in computing radiant heat transfer between parallel plates of polished aluminum and as-rolled Inconel, found that the slight deviations of these materials from true gray-body emission caused the heat-transfer rates computed from total emittance values to be up to 29 percent lower than those computed from spectral-emittance data. Errors for ceramic materials and oxidized metals, which in general depart much more from gray-body emission, would undoubtedly be considerably larger.

EXPERIMENTAL PROCEDURE

The nearest attainable approach to an ideal black body that can be devised for laboratory use is an almost completely closed cavity in an opaque body, the walls of which are at a uniform temperature. The difficulties in maintaining temperature uniformity increase with the size of the cavity, and a small opening focused on a spectrometer requires that the spectrometer slit also be kept small which in turn involves use of high amplifier gain and slow scanning speeds.

To minimize these difficulties it was decided to use a recrystallized silicon carbide rod (Globar) as a secondary standard, which was compared against a cavity-type, laboratory black body.

A double-beam infrared spectrophotometer with a sodium chloride prism was used for all measurements. Ordinarily the instrument is used for transmission measurements with its external optics arranged schematically as shown in figure 1(a). A Nernst glower N was viewed by two pairs of mirrors that focus images of the source on the monochromator slits. The instrument records the ratio of the energies of the two beams, which depends upon the absorption of a transmission specimen S.

For emission measurements the external optics were modified as shown in figure 1(b). The mirror M was rotated to produce an image of the specimen B or the standard G on the slit. The effective apertures of the two beams were then different, but, because the path lengths were approximately equal, the absorption by atmospheric carbon dioxide and water in the two paths was nearly balanced.

The design of the laboratory black body is shown in figure 2. The core was made of graphite and was heated by passing an electric current

through it. During a test nitrogen flowed into the Vycor cylinder sur-
rounding the cavity in the graphite. This reduced, but did not eliminate,
oxidation of the graphite. The temperature of the black body was meas-
ured by means of a base-metal thermocouple, as is shown in the figure.
The temperature was maintained within ±3° of the desired temperature by
manual adjustment of the power input.

The temperature of the silicon carbide heating element was measured
by means of a base-metal thermocouple inserted into a small hole about
1/8 inch deep that had been drilled into the element near its center by
means of a Cavitron (ref. 4). This temperature was also maintained
within ±3° of that desired by manual adjustment of the power input.

Two different metals were studied, type 321 stainless steel and
Inconel. Type 321 stainless steel is a titanium-stabilized 18-percent-
chromium, 8-percent-nickel austenitic stainless steel. Inconel is nomi-
nally 80 percent nickel, 14 percent chromium, and 6 percent iron.

The metal specimens were in the form of 0.050-inch strips 6 inches
long and 3/4 inch wide at the ends. The center portion of each specimen
was necked down to a width of 0.300 inch for a distance of 2.4 inches.
A hole 1 millimeter in diameter (approx. 0.040 inch) and about 0.045 inch
deep was drilled near the center of the necked-down portion of each
specimen. A base-metal thermocouple having a bead about 0.038 inch in
diameter was inserted into this hole and peened in before the final sur-
face treatment of the specimen.

Surface treatments included electropolishing, sandblasting accom-
plished by means of 40-mesh glass sand and air at a pressure of 40 psi,
oxidation in air at 1,800° F for 1/2 hour following electropolishing,
oxidation in air at 1,800° F for 1/2 hour following sandblasting, coating
with NBS coating N-143, and coating with NBS coating A-418.

The electropolishing and coating treatments were applied only to
the necked-down portion of a specimen. The ends of the oxidized and
coated specimens were sandblasted following the respective treatments
in order to provide good contact for the electrodes.

The two ceramic coatings have been completely described in previ-
ous reports (refs. 5 and 6). Coating N-143 consists of a boron-free
barium beryllium silicate frit with a refractory mill addition of cerium
oxide. It is light cream in color. Coating A-418 consists of an alkali-
free barium borosilicate frit with a refractory mill addition of chromic
oxide. It is dark green in color.

For most of the tests the coatings were applied at a thickness of
approximately 0.002 inch, which is the thickness at which they are nor-
mally applied in service. For a few tests coatings of greater thickness
up to 0.0086 inch were used.

No correction was made for the thermal gradient through the coating of normal (0.002-inch) thickness, because it was believed that the gradient was smaller than the normal fluctuation in temperature of the metal specimen (less than the normal $\pm 3^\circ$). In reference 7, measured thermal gradients in ceramic coatings on the order of 1° F per mil of thickness were reported.

The metal specimens were heated by passing an electric current through them, the power being supplied through a high-amperage, low-voltage welding transformer. The temperature was maintained to within $\pm 3^\circ$ of that desired by manual adjustment of the power input.

In making a determination the specimen and standard were mounted side by side, as indicated in figure 1(b), and were brought to the same temperature. Mirror M_1 was then adjusted so as to focus the image of the standard on the slit of the monochromator, and a curve representing emission of the standard as a ratio of that of the Nernst glower was obtained over the wavelength range of 1.25 to 15 microns. Next, mirror M_1 was shifted slightly to focus the image of the specimen on the slit, and the measurement was repeated. The ratio of the heights of the two curves, corrected for the small difference introduced by the shift in angle of the mirror, was then computed wavelength by wavelength over the entire range.

The first series of measurements was made with the black body as the standard and the silicon carbide element as the specimen. The resulting curves represented the spectral emittance of the silicon carbide heating element at the test temperatures.

At the end of this series of tests the graphite black body was very badly oxidized at the exposed ends where the electrodes were attached.

The second series of tests was made with the silicon carbide element as the standard and a metal strip as the specimen. In each case the curve obtained as the ratio of the heights of the curves for the specimen and standard was the ratio of the spectral emission of the specimen to that of the standard. To obtain the spectral-emittance curve for the specimen, the curve thus obtained was converted through multiplying selected values, wavelength by wavelength, by the spectral emittance of the silicon carbide element. Typical resulting curves made at $1,800^\circ$ F are shown in figure 3. Determinations were made at temperatures of 900°, $1,200^\circ$, $1,500^\circ$, and $1,800^\circ$ F.

The distribution of emission of a black body according to wavelength, expressed as a fraction of the emission at the maximum point and computed from the Planck radiation equation, was plotted as a function of wavelength times absolute temperature λT for values of λT from 0.05 to 2.0, as shown in figure 4. A corresponding curve for each specimen was

computed by multiplying the spectral emittance at each increment of λT by the corresponding emission of the black body. The total emittance was then computed from the area under the emission curve of the specimen as measured with a planimeter and expressed as a fraction of the area under the black-body curve.

Several techniques were considered for measuring the surface temperature directly on specimens with the thicker coatings, but the experimental difficulties of obtaining accurate surface temperatures of coatings in this thickness range were believed to be too great. The method finally selected was to measure the power input required to maintain the specimen at a definite metal temperature and then to compute the temperature drop through the coating from a knowledge of the thermal conductivity of the coating layer, its thickness, and the surface area of the specimen.

The power-input measurements were made on metal specimens of the same design as was used for emittance measurements. These specimens also contained a thermocouple peened into a hole near the center. Two small areas, about $1\frac{1}{2}$ inches apart and about equally spaced on either side of the center of the necked-down portion of the specimen, were cleaned by sandblasting; a light scratch, perpendicular to the axis of the specimen, was made in each cleaned area. Fine Nichrome wires were laid in the scratches and spot-welded to the specimen at those locations. Before making a test the distance between these two wires was measured to the nearest 0.01 inch by means of a vernier caliper, and the width and thickness of the specimen was measured to the nearest 0.001 inch by means of a micrometer caliper.

In making a test the specimen was heated by passing an electric current through it, as in the emittance measurements. One lead from the power supply passed through the coil of a current transformer that was connected to an ammeter. The two Nichrome wires welded to the specimen were connected to the leads of a vacuum-tube voltmeter, and the thermocouple leads were connected to a precision portable potentiometer. The power input was adjusted until the temperature of the specimen was stabilized at the desired temperature, the amperage in the circuit was recorded to the nearest 0.1 ampere, and the voltage across the measured gage length was recorded to the nearest 0.01 volt. Tests were made at temperatures of 900°, $1,200^{\circ}$, $1,500^{\circ}$, and $1,800^{\circ}$ F.

The power input to the specimen over the measured gage length was computed from the measured amperage and voltage; the error due to power factor was assumed to be negligible because the inductance and capacitance of the circuit elements were very low. The surface area of the measured gage length was computed, and the power input was expressed as watts/sq cm of surface area which was then converted to Btu/sq ft hr.

There was some heat loss due to conduction through the ends of the specimens, but this was considered to be negligibly small because no thermal gradient could be detected by eye within the measured gage length.

The thermal conductivity of the coatings was not accurately known, but thermal conductivities of other ceramic coatings had been measured previously and were found to be in the range 6 to 9 Btu in./sq ft hr $^\circ$F. A thermal-conductivity value of 7.5 was assumed for the coatings, and the thermal gradient, in $^\circ$F/mil, was computed from the measured rate of heat flow. In the emittance determinations on specimens having thick coatings, the temperature of the specimen was corrected for the computed gradient.

PRESENTATION AND DISCUSSION OF DATA

The curves for the spectral emittance of the silicon carbide heating element at temperatures of 900°, $1,200^\circ$, $1,500^\circ$, and $1,800^\circ$ F are shown in figure 5. The values are in qualitative agreement with those obtained by Silverman (ref. 8) and Brügel (ref. 9) but tend to be somewhat lower. The precision of the measurements as determined from duplicate tests was found to be ±2 percent at wavelengths below about 5 microns and ±1 percent at longer wavelengths. Within these limits no temperature dependence of emittance was found for regions sufficiently remote from the minima at about 9 and 12 microns, respectively. These minima are temperature sensitive, however, and occur at longer wavelengths at higher temperatures. This temperature shift for the 9-micron minima is not evident in figure 5 but can be seen when data are included for temperatures above and below those for which data are shown in the figure.

The minima at about 12 microns corresponds to a peak in the Raman spectrum of silicon carbide as reported by Narayanan (ref. 10), but no band near 9 microns has been observed in the infrared absorption, reflection, or Raman spectra of silicon carbide. The various forms of silica are known to have strong reflection bands near 9 microns, due to the asymmetric stretching of the Si-O-Si bonds, and these bands seem to shift to longer wavelengths as temperature is increased. Silica is formed by the oxidation of silicon carbide and is probably present in sufficient quantity to account for the minima at about 9 microns.

The observation of Pirani (ref. 11) that total emittance of a mixture of silicon carbide and clay decreases with increasing temperature is consistent with a spectral emittance that is independent of, or even slightly increasing with, temperature because as the temperature is increased the peak of the Planck emission curve moves to shorter wavelengths where the spectral emittance of the silicon carbide is lower.

The infrared reflection spectrum of silicon carbide as published by Coblentz (ref. 12) and later by Schaefer and Thomas (ref. 13) showed nothing of significance except a strong absorption peak at 12 microns and a maximum at 10 microns. Ramdas (ref. 14) recently redetermined the absorption spectrum between 1 and 20 microns for a number of modifications of silicon carbide, using plates ranging between 0.14 and 1.0 millimeter in thickness. He found a very strong absorption band centered near 12 microns.

The data on spectral emittance of the metal specimens at $900°$, $1,200°$, $1,500°$, and $1,800°$ F for wavelengths at 1/2-micron intervals from 1.5 to 15 microns are shown in table I. The total-emittance values computed from these spectral-emittance data are shown in table II.

The spectral-emittance curves for type 321 stainless steel at $900°$ F are shown in figure 6(a). The general features of interest in these curves are the relatively flat low curve for the electropolished metal, the relatively flat but somewhat higher curve for the sandblasted metal, the much higher curves that fall to lower values at the longer wavelengths for the oxidized specimens, and the steepness between 2 and 8 microns of the curves for the coated specimens. The emittance of the specimen coated with A-418 was higher than that of the specimen coated with N-143 at all wavelengths.

The curves for stainless steel at $1,800°$ F in figure 6(b) are similar to those at $900°$ F but are all displaced upward. The polished and sandblasted specimens oxidized too rapidly at this temperature to permit evaluation in the unoxidized condition.

The curves for Inconel at $900°$ F for the polished and sandblasted condition, shown in figure 6(c), are approximately the same as those for the type 321 stainless steel, and the curves for the coated specimens are similar in shape to the corresponding curves for stainless steel but are displaced upward. This is particularly true of the curve for the specimen coated with N-143. The curve for the oxidized specimens of Inconel is quite different from the corresponding curves for oxidized type 321 stainless steel. The polished oxidized specimen had much higher emittance at all wavelengths than did the sandblasted oxidized specimen, and the curves for the oxidized specimens do not show the marked decrease in emittance at longer wavelengths noted for the type 321 stainless steel specimens.

The curves for Inconel at $1,800°$ F, shown in figure 6(d), are similar in shape to the corresponding curves for Inconel at $900°$ F but all are displaced upward. The polished and sandblasted specimens oxidized too rapidly at this temperature to permit evaluation in the unoxidized condition. The Inconel specimen coated with N-143 had appreciably higher emittance at all wavelengths than did the corresponding stainless steel

specimen tested at this temperature, but the Inconel specimen coated with A-418 had only slightly higher emittance than did the corresponding stainless steel specimen. The polished oxidized specimen had appreciably higher emittance at all wavelengths than did the sandblasted oxidized specimen and the A-418 coated specimen had a higher emittance than did the N-143 coated specimen. This was also observed at 900° F.

In general, the shape of the spectral-emittance curves for specimens coated with A-418 was similar to that for specimens coated with N-143. The normal spectral emittance for the coated specimens increased rapidly with wavelength from 1.5 microns to a maximum at about 9 microns, decreased to a minimum at about 10.5 microns, and then increased to a second maximum at about 13.5 microns.

The shape of the spectral-emittance curves of the coated specimens in general agrees with that found by De Corso and Coit (ref. 15) for Inconel and the A-417/235 coating, but their spectral bands were too broad to reveal any fine structure. The curves are also in qualitative agreement with the spectral-reflectance curve for white porcelain enamel published by Smith (ref. 16).

The shape and general height of the spectral-emittance curves for the polished metals are in qualitative agreement with the spectral-reflectance curve for polished aluminum (also ref. 16). None of the spectral-emittance curves for Inconel agree even qualitatively with that determined by De Corso and Coit (ref. 15) for as-rolled Inconel. Their curve shows an emittance of 0.8 at about 2 microns which falls to about 0.2 at about 12 microns.

The higher emittance of the sandblasted oxidized Inconel as compared with that of the polished oxidized Inconel called for an explanation. The oxide layers were examined by X-ray diffraction. Only chromic sesquioxide (Cr_2O_3) was identified on the oxide layer on the sandblasted specimen, but Cr_2O_3, iron sesquioxide (Fe_2O_3), and nickel oxide (NiO) were found in the oxide layer on the electropolished specimen. From the relative heights of the peaks it was estimated that both Fe_2O_3 and NiO were present in substantially greater amounts than was Cr_2O_3. Published values (ref. 17) for total emissivity at 2,000° F of 0.73 for Cr_2O_3, 0.89 for Fe_2O_3, and 0.86 for NiO indicate that this difference in composition could account for part, but not all, of the observed effect.

Examination of tapered sections of the oxidized specimens revealed that the oxide-metal interface was much rougher on the sandblasted than on the electropolished specimen, as would be expected. The oxide layer on the sandblasted specimen appeared to be very much thinner than that on the electropolished specimen. This was confirmed by weight-gain

oxidation tests, results of which are shown in figure 7. After 30 minutes in air at 1,800° F, the sandblasted specimen had gained only about half as much weight as had the electropolished specimen. When the much larger surface area per unit of nominal area of specimen is considered, the observed difference in thickness will be much greater. Computations indicated that the oxide layer on the sandblasted specimen would not exceed about 3 microns in thickness, even if the true surface area were no greater than the nominal specimen area. Thin oxide films are known to be partially transparent to infrared radiation, hence it is believed that the observed difference in thickness of the oxide layers on the sandblasted and electropolished specimens satisfactorily accounts for the observed difference in spectral emittance, since this property was influenced to varying degrees by emission from the substrate metal.

Each value in table I is computed from the results of four different comparisons made on the spectrophotometer: (1) The Nernst glower against the black body, (2) the Nernst glower against the silicon carbide heating element, both used in calibrating the silicon carbide standard, (3) The Nernst glower against the specimen, and (4) the Nernst glower against the silicon carbide standard, both used in making a determination. The reproducibility of each comparison, determined from duplicate runs, was on the order of ±2 percent at wavelengths below about 5 microns and ±1 percent at longer wavelengths. If the errors were all in the same direction, this could result in a maximum error of ±8 percent in the values in table I. If the errors are random, as is believed to be the case, they would not be expected to exceed ±4 percent. These random errors may arise from any of the following causes, among others: (1) temperature fluctuations in the Nernst glower caused by slight variations in the line voltage; (2) temperature fluctuation in the specimen or silicon carbide standard within the ±3-percent zone to which it is controlled, (3) temperature gradients over the surface of the specimen or standard in the area from which radiant energy is accepted for measurement, and (4) slight variations in the sensitivity of the detector or in the amplifier of the spectrophotometer. There also may be present some constant errors due to such factors as failure of the energy emitted by the black body to conform exactly to the Planck radiation law, slight differences in absorption or reflection along the two optical paths in the instrument, and temperature differences due to errors in the calibration of thermocouples. However, such constant errors are believed to be small.

The data in table I (plotted in fig. 6), show a consistent trend toward an increase in spectral emittance with an increase in temperature regardless of surface finish or wavelength. The data for total emittance in table II show a corresponding trend for the uncoated bare or oxidized specimens. This is in agreement with the findings in references 7, 15, 18, 19, and 20. The coated specimens, however, show a slight but definite trend toward decrease in total emittance with an increase in temperature. This is in agreement with the findings in

references 7 and 19 but is in conflict with the data reported by Bennett
in reference 21. However, Bennett's data covered only the wavelength
range of 0.7 to 1.2 microns, and hence can be considered to be closer
to spectral than to total emittance. On this basis his findings check
the data in table I.

It may appear as a contradiction in the data on the effect of tem-
perature upon the emittance of coated specimens that, on the one hand,
spectral emittance increases with temperature at all wavelengths and,
on the other hand, total emittance decreases with an increase in tem-
perature. This apparent anomaly can be explained by the shape of the
spectral-emittance curves for the coated specimens. The spectral emit-
tance of the coated specimens increased sharply with wavelength over
the region of 1.5 to 5 microns. At the temperatures used in this inves-
tigation the peak of the Planck emission curve for a black body lies in
this spectral region. The shift of this peak with temperature toward
shorter wavelengths, where the spectral emittance of the coated specimen
is lower, is more than enough to compensate for the small increase with
temperature of the spectral emittance at all wavelengths. Hence for
these specimens the total emittance decreases with an increase in tem-
perature, not as a result of the change in spectral emittance with tem-
perature but, as a result of the shift with temperature in the relative
spectral distribution of the energy emitted by the specimen and by a
black body at the same temperature.

Figure 4 shows the curves for the emission ratio for a black body
and for specimens coated with coating N-143, at temperatures of 900°
and $1,800^\circ$ F, plotted as a function of λT. These curves show that at
values of λT up to about 0.7 the coated specimen tested at 900° F had
the higher emittance, while for higher values of λT the coated speci-
men at $1,800^\circ$ F had the higher emittance. The total emittance is pro-
portional to the area under the curve for each specimen, and it can be
seen that this area is appreciably larger for the specimen at 900° F
than for the specimen at $1,800^\circ$ F.

The data on the thermal gradients computed from the power-input
measurements are shown in table III. The indicated difference in ther-
mal gradients in coating N-143 as applied to Inconel and to type 321
stainless steel is undoubtedly due to the effect of the underlying metal
on the emittance of the coating. All of the power-input measurements
were made on specimens having a coating approximately 2 mils thick. The
curves in figure 6 indicate that at this thickness the emittance of the
coated specimens was affected by the alloy to which the coating was
applied as well as by the composition of the coating, and that the effect
of the underlying metal was greater for coating N-143 than for
coating A-418.

The power-input measurements showed that the power required to maintain an Inconel specimen at 1,800° F was about 20 percent greater for a specimen coated with A-418 than for a bare, as-rolled specimen of the same alloy. This indicates that the coating increased heat dissipation from the coated specimen as compared with a bare specimen of the same alloy. When the coated and bare Inconel specimens were subjected to the same power input of 40,000 Btu/sq ft hr, the coated specimen reached an equilibrium temperature 105° F lower than that reached by the bare specimen.

The effect of the thickness of coating on spectral emittance is shown in figure 8. Figure 8(a) shows that of the specimens coated with A-418, the stainless steel specimen with a coating 2.2 mils thick had the lowest emittance at all wavelengths, the Inconel specimen with a coating 2.0 mils thick had the next lowest emittance, and there was little difference in the emittances of the Inconel specimens having coatings 4.8 and 5.8 mils thick and the stainless steel specimen having a coating 5.5 mils thick. This indicates that the coating is opaque when applied at a thickness of about 5 mils, because at this thickness the effect of the underlying metal practically disappears and the effect of increasing the thickness from 4.8 to 5.8 mils is very slight. Figure 8(b) shows similar data for specimens coated with N-143, and again the effect of the underlying metal is very marked when the coating is applied at a thickness of about 2 mils but nearly disappears at thicknesses of about 5 mils or greater. Specimens coated with 5 mils or more of coating A-418 or N-143 had nearly the same spectral emittance at wavelengths greater than about 5 microns, while at wavelengths below 5 microns the A-418 coated specimens had the higher emittance.

The specimens coated with 5 mils or more of A-418 or N-143 had indicated spectral emittances of more than 1.0 at wavelengths in the vicinity of 8.5 and 14 microns. This result is obviously in error since by definition a black body emits the maximum possible amount of radiant energy at all wavelengths at a given temperature. The error might be due to an accumulation of errors of the type mentioned previously, but part of it is undoubtedly due to the fact that the radiant energy emitted by the coated specimen originated in a layer of coating material having a temperature gradient, and not at the surface of the coating. Because of the thermal gradient through the coating the average temperature of this volume, within which the radiant energy originates, will be higher than the temperature of the outer surface of the coating, and erroneously high emittance values will be obtained. This error could be eliminated by measuring the emittance of specimens held at a uniform temperature under conditions such that no thermal gradient exists in the coating. It cannot be eliminated under the experimental conditions that were used in this study, but corrections could be estimated.

National Bureau of Standards,
    Washington, D. C., November 8, 1957.

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TABLE I.- SPECTRAL EMITTANCE DATA FOR METAL SPECIMENS

Surface treatment	Temperature, °F	Spectral emittance at wavelength, micron, of -																											
		1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0
Stainless steel																													
Electropolished	900	----	0.12	0.15	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.12	0.12	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.10	0.10	0.09
	1,200	0.29	.27	.25	.24	.22	.21	.19	.18	.17	.15	.15	.15	.14	.14	.14	.14	.13	.13	.13	.13	.12	.12	.12	.12	.11	.11	.11	.10
Sandblasted	900	----	----	0.34	0.36	0.38	0.39	0.39	0.40	0.41	0.42	0.41	0.40	0.39	0.38	0.39	0.41	0.41	0.40	0.39	0.39	0.40	0.40	0.41	0.41	0.42	0.42	0.41	0.40
	1,200	0.34	0.36	.37	.38	.41	.41	.41	.40	.41	.40	.38	.38	.38	.39	.40	.41	.41	.41	.42	.41	.41	.40	.42	.44	.44	.44	.43	.42
Electropolished oxidized	900	----	0.63	0.66	0.68	0.69	0.69	0.67	0.64	0.65	0.68	0.68	0.69	0.70	0.73	0.76	0.77	0.75	0.69	0.65	0.63	0.59	0.54	0.49	0.43	0.38	0.34	0.34	0.34
	1,200	----	.60	.66	.69	.70	.68	.68	.65	.68	.69	.71	.72	.73	.75	.74	.75	.74	.73	.70	.67	.64	.59	.52	.46	.41	.37	.36	.36
	1,500	0.70	.76	.78	.79	.78	.76	.74	.68	.73	.74	.76	.77	.78	.78	.79	.80	.78	.76	.74	.71	.71	.63	.58	.51	.46	.42	.40	.39
	1,800	.67	.73	.75	.77	.77	.77	.76	.70	.77	.78	.80	.78	.77	.76	.76	.77	.75	.72	.72	.66	.64	.64	.57	.54	.49	.44	.42	.40
Sandblasted oxidized	900	----	0.52	0.59	0.65	0.67	0.69	0.69	0.69	0.70	0.71	0.70	0.70	0.71	0.73	0.77	0.83	0.82	0.82	0.84	0.86	0.85	0.81	0.78	0.75	0.72	0.68	0.65	0.63
	1,200	0.65	.65	.68	.72	.75	.74	.75	.75	.75	.74	.73	.73	.75	.75	.78	.83	.84	.84	.85	.86	.86	.86	.83	.80	.77	.75	.72	.69
	1,500	.65	.65	.68	.72	.73	.74	.75	.76	.76	.76	.75	.75	.75	.76	.78	.83	.84	.84	.84	.84	.84	.84	.81	.78	.76	.73	.70	.67
	1,800	.65	.71	.77	.79	.82	.82	.80	.76	.77	.76	.75	.75	.75	.77	.81	.84	.85	.85	.85	.86	.87	.87	.86	.82	.82	.81	.76	.71
Coated A-418, appr. 2 mils	900	----	0.29	0.35	0.41	0.49	0.56	0.63	0.69	0.74	0.77	0.79	0.81	0.83	0.84	0.85	0.85	0.82	0.78	0.77	0.77	0.78	0.80	0.84	0.86	0.88	0.89	0.89	0.88
	1,200	0.51	.36	.41	.46	.53	.58	.61	.70	.74	.77	.77	.81	.83	.84	.85	.85	.81	.78	.77	.77	.78	.80	.86	.86	.88	.93	.93	.90
	1,500	.38	.45	.49	.55	.64	.69	.71	.78	.82	.84	.86	.88	.89	.89	.90	.90	.88	.85	.83	.82	.82	.83	.87	.89	.90	.89	.92	.92
	1,800	.39	.46	.54	.60	.66	.71	.75	.78	.82	.85	.86	.89	.89	.90	.93	.95	.94	.88	.86	.83	.82	.84	.89	.93	.95	.91	.89	.87
Coated N-143, appr. 2 mils	900	----	0.08	0.14	0.20	0.25	0.31	0.35	0.44	0.50	0.52	0.54	0.55	0.58	0.60	0.61	0.61	0.59	0.56	0.57	0.60	0.63	0.65	0.68	0.69	0.69	0.68	0.68	0.66
	1,200	0.04	.14	.22	.27	.31	.34	.39	.49	.54	.56	.59	.60	.63	.65	.66	.66	.62	.60	.60	.61	.64	.66	.68	.69	.70	.69	.69	.67
	1,500	.08	.16	.23	.29	.34	.38	.43	.54	.60	.63	.65	.66	.67	.69	.69	.70	.66	.63	.62	.64	.66	.67	.68	.69	.70	.72	.71	.69
	1,800	.15	.22	.30	.36	.43	.47	.51	.58	.63	.66	.67	.68	.69	.70	.73	.73	.69	.65	.65	.65	.67	.70	.73	.76	.78	.75	.74	.71
Inconel																													
Electropolished	900	----	0.20	0.18	0.17	0.17	0.17	0.16	0.16	0.15	0.15	0.15	0.14	0.14	0.13	0.14	0.13	0.12	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.09	0.09	0.08
	1,200	----	.30	.24	.21	.19	.18	.17	.16	.17	.16	.15	.15	.15	.15	.15	.15	.15	.14	.14	.14	.14	.14	.13	.13	.13	.13	.12	.12
Sandblasted	900	----	0.34	0.34	0.35	0.36	0.37	0.36	0.35	0.34	0.33	0.33	0.33	0.33	0.33	0.34	0.36	0.35	0.35	0.35	0.36	0.36	0.36	0.35	0.35	0.35	0.35	0.35	0.35
	1,200	0.41	.38	.41	.41	.40	.39	.39	.38	.37	.36	.36	.35	.35	.35	.36	.37	.36	.36	.36	.36	.37	.37	.37	.37	.39	.39	.39	.38
Electropolished oxidized	900	----	0.58	0.57	0.59	0.60	0.60	0.59	0.59	0.59	0.58	0.57	0.62	0.70	0.75	0.78	0.78	0.73	0.70	0.72	0.73	0.73	0.74	0.75	0.76	0.79	0.81	0.81	0.80
	1,200	0.58	.60	.60	.61	.61	.63	.62	.61	.65	.59	.59	.64	.71	.75	.78	.79	.79	.80	.78	.77	.77	.77	.78	.79	.81	.82	.84	.82
	1,500	.68	.72	.72	.69	.71	.69	.66	.65	.65	.64	.66	.68	.74	.78	.78	.79	.78	.78	.78	.76	.76	.78	.79	.80	.81	.82	.82	.83
	1,800	.70	.76	.76	.75	.79	.76	.72	.71	.69	.68	.68	.70	.74	.77	.79	.80	.78	.78	.78	.79	.81	.83	.87	.87	.87	.85	.85	.84
Sandblasted oxidized	900	----	0.44	0.44	0.47	0.49	0.51	0.53	0.55	0.55	0.56	0.56	0.62	0.66	0.68	0.69	0.70	0.67	0.61	0.60	0.58	0.58	0.54	0.54	0.52	0.52	0.52	0.52	0.52
	1,200	0.50	.51	.51	.51	.53	.54	.55	.57	.57	.56	.56	.63	.66	.67	.68	.67	.65	.61	.60	.58	.57	.55	.52	.51	.52	.53	.53	.53
	1,500	.49	.51	.51	.53	.55	.56	.57	.57	.58	.58	.59	.65	.67	.69	.70	.70	.61	.65	.65	.61	.63	.56	.54	.53	.53	.53	.55	.55
	1,800	.52	.55	.56	.57	.60	.60	.58	.58	.59	.60	.59	.63	.64	.65	.65	.66	.66	.62	.62	.57	.59	.54	.55	.53	.52	.52	.51	.51
Coated A-418, appr. 2 mils	900	0.22	0.22	0.39	0.46	0.53	0.58	0.64	0.73	0.78	0.82	0.84	0.86	0.88	0.90	0.90	0.90	0.88	0.85	0.85	0.83	0.83	0.84	0.88	0.91	0.84	0.95	0.96	0.96
	1,200	0.33	.39	.44	.51	.55	.61	.66	.76	.76	.82	.85	.87	.88	.89	.89	.90	.87	.82	.81	.80	.82	.83	.87	.90	.88	.92	.93	.92
	1,500	.40	.46	.51	.57	.64	.68	.70	.78	.83	.84	.88	.89	.89	.90	.91	.91	.88	.84	.83	.82	.82	.82	.88	.90	.88	.93	.93	.91
	1,800	.44	.51	.58	.62	.69	.73	.75	.80	.84	.87	.88	.91	.90	.92	.94	.91	.93	.88	.86	.83	.83	.85	.91	.94	.91	.93	.88	.88
Coated N-143, appr. 2 mils	900	----	0.17	0.26	0.34	0.39	0.43	0.48	0.60	0.65	0.68	0.69	0.71	0.75	0.79	0.82	0.82	0.72	0.69	0.71	0.74	0.77	0.80	0.83	0.84	0.85	0.85	0.84	0.81
	1,200	0.18	.24	.31	.37	.42	.48	.54	.66	.69	.73	.76	.77	.80	.83	.85	.84	.78	.73	.74	.77	.80	.86	.89	.87	.88	.88	.87	.86
	1,500	.23	.28	.35	.42	.46	.49	.55	.70	.76	.78	.81	.83	.84	.85	.88	.86	.81	.77	.77	.78	.80	.83	.86	.87	.87	.86	.86	.85
	1,800	.26	.33	.41	.46	.53	.58	.61	.72	.78	.81	.83	.85	.86	.88	.91	.91	.85	.79	.77	.78	.78	.81	.87	.92	.92	.87	.87	.86

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TABLE II.- TOTAL-EMMITTANCE DATA FOR METAL SPECIMENS

AND COATINGS

(a) Data for specimens

Specimen type	Total emittance, percent, for temperature, °F, of -			
	900	1,200	1,500	1,800
Electropolished stainless steel	10	18	--	--
Sandblasted stainless steel	34	38	--	--
Electropolished oxidized stainless	65	69	74	72
Sandblasted oxidized stainless steel	68	75	70	74
A-418 coated stainless steel	63	58	63	61
N-143 coated stainless steel	38	37	34	36
Electropolished Inconel	11	18	--	--
Sandblasted Inconel	31	37	--	--
Electropolished oxidized Inconel	60	61	68	73
Sandblasted oxidized Inconel	52	52	54	55
A-418 coated Inconel	68	63	64	64
N-143 coated Inconel	55	50	51	49

TABLE II.- TOTAL-EMITTANCE DATA FOR METAL SPECIMENS

AND COATINGS - Concluded

(b) Data for coatings at 1,200° F

Material	Thickness of coating, mils	Total emittance, percent
A-418 coating		
Inconel	2	64
Inconel	4.8	71
Inconel	5.8	69
Stainless	2.2	59
Stainless	5.5	70
N-143 coating		
Inconel	2.6	55
Inconel	4.9	66
Inconel	8.6	61
Stainless	2.2	40
Stainless	5.1	62

TABLE III.- THERMAL GRADIENTS FOR CERAMIC COATED SPECIMENS

COMPUTED FROM POWER-INPUT MEASUREMENTS

[Specimens had coating approximately 2 mils thick]

Temperature, °F	Thermal gradient, °F/mil, for -			
	A-418 on -		N-143 on -	
	Inconel	Stainless steel	Inconel	Stainless steel
900	1.02	1.03	0.97	1.02
1,200	2.00	1.95	1.74	1.95
1,500	3.37	3.39	3.10	3.33
1,800	5.55	5.47	5.11	5.19
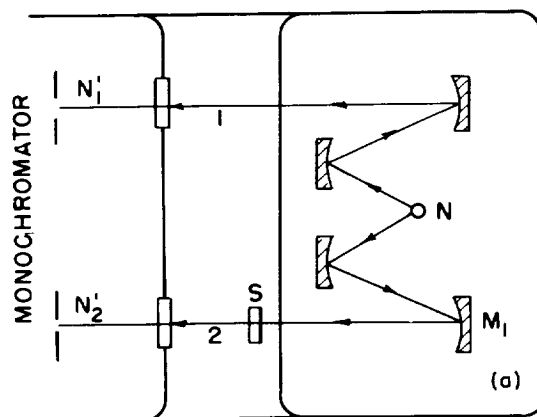
(a) Setup used for transmission measurements. N, Nernst glower source; M_1, spherical mirror; S, transmission specimen; N_1 and N_2, images of source focused on entrance slits of monochromator.
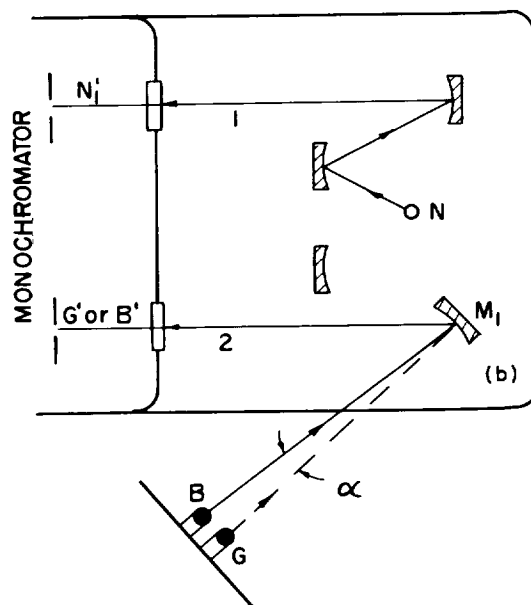
(b) Setup used for emittance measurements. Mirror M_1 is shifted on its axis to focus alternately images B' or G' of specimen B or standard G on entrance slit for one beam of monochromator while image N' of Nernst glower N is focused on other entrance slit of monochromator.

Figure 1.- Schematic diagram of external optics of spectrometer used for transmission and emittance measurements.

SLOT, 2mm Wide x 24mm Long

SLOT, 1.5 mm Wide x 20mm Long

THERMOCOUPLE

$D\frac{1}{2}"$

$6"$

$4"$

$D\frac{3}{4}"$

$D1\frac{1}{2}"$

N_2

GRAPHITE

VYCOR

ASBESTOS PAPER
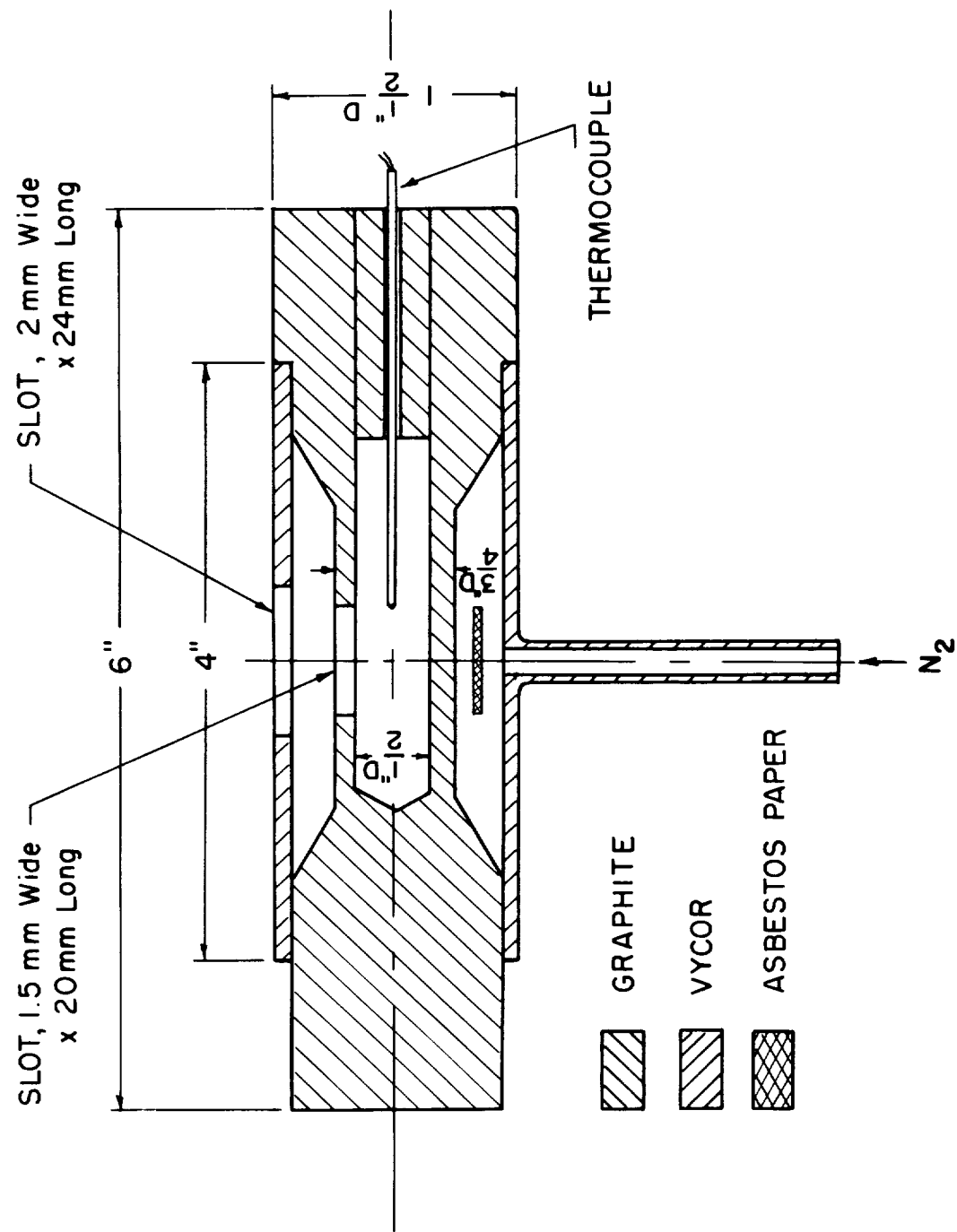
Figure 2.- Sectional view of graphite black-body standard.
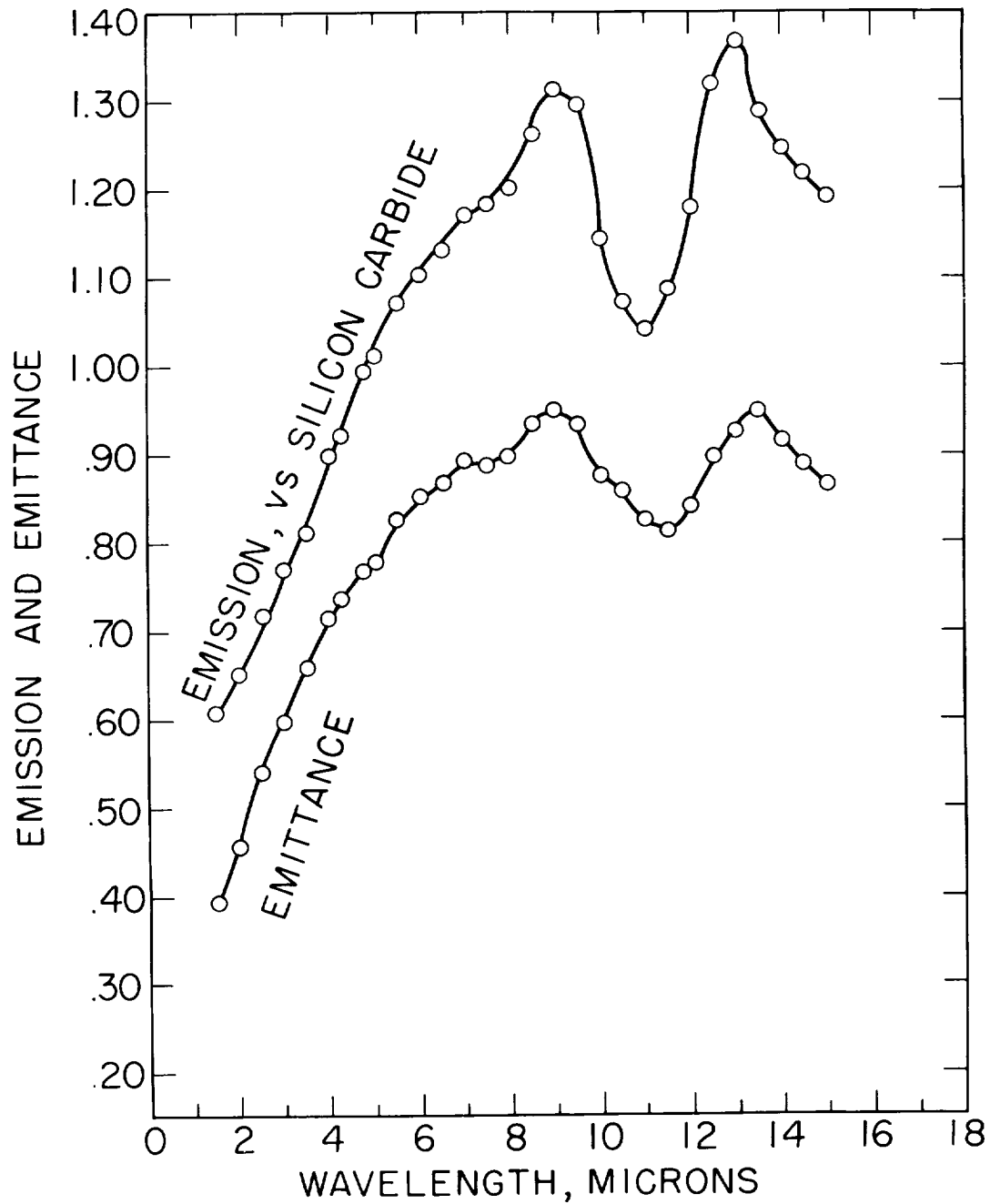
Figure 3.- Emission and emittance curves for A-418 coated stainless
steel specimen at 1,800° F. Curves obtained from ratio of emission
of stainless steel to that of silicon carbide as explained in main
text.
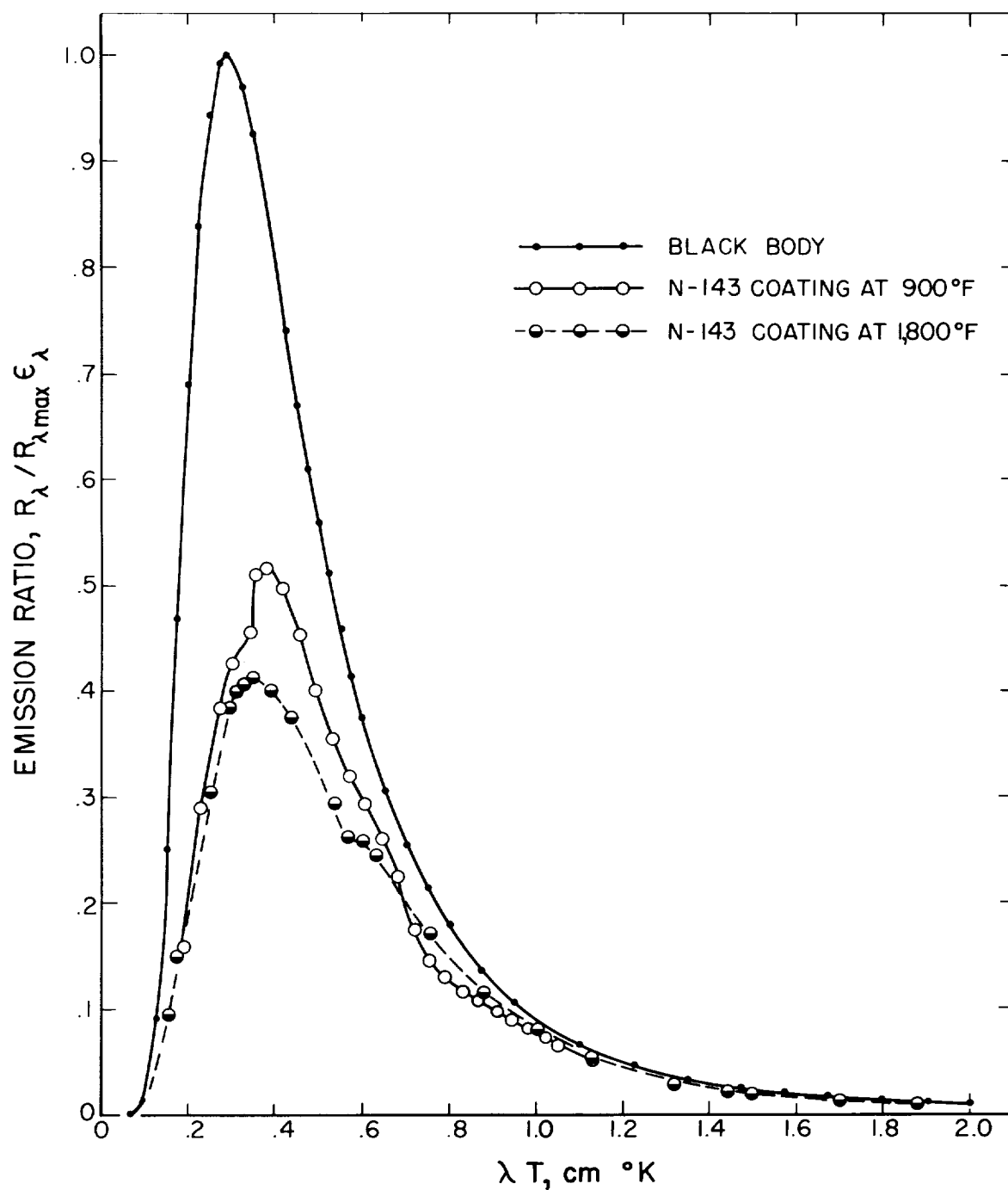
Figure 4.- Planck emission curve for a black body and similar curves for two coated specimens plotted as a function of absolute temperature times wavelength λT. Total emittance of coated specimen is ratio of area under curve for specimen to area under curve for black body.
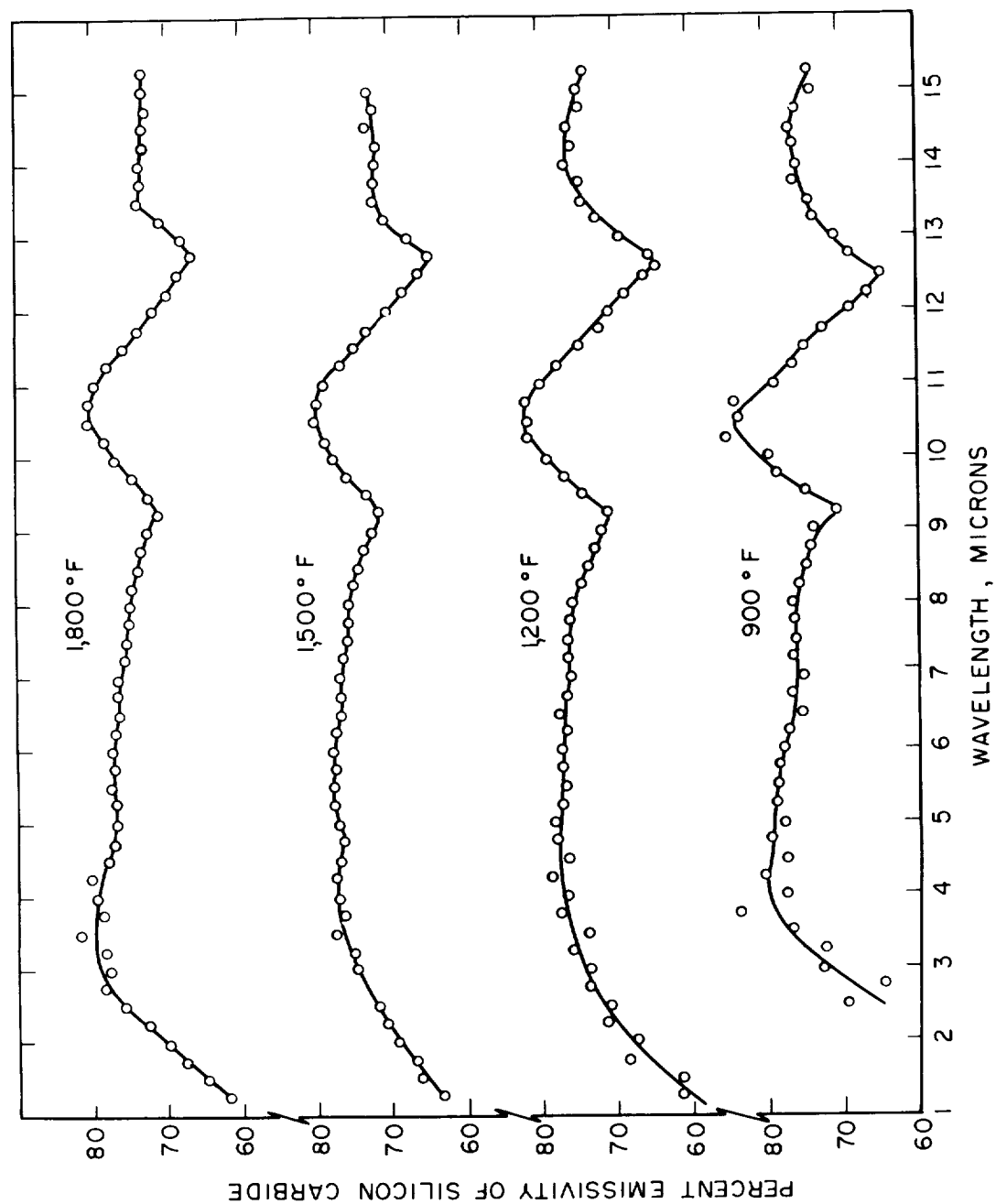
Figure 5.- Spectral-emittance curves of silicon carbide heating element at 900°, 1,200°, 1,500° and 1,800° F.
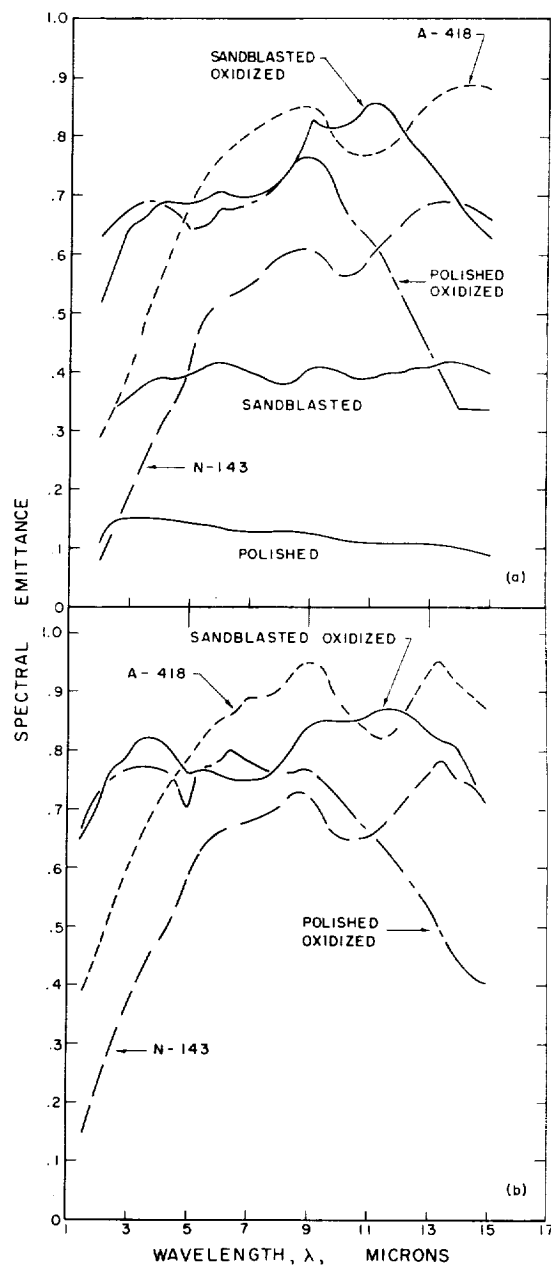
(a) Stainless steel; 900° F.

(b) Stainless steel; 1,800° F.

Figure 6.- Spectral-emittance curves for specimens with different surface treatments.
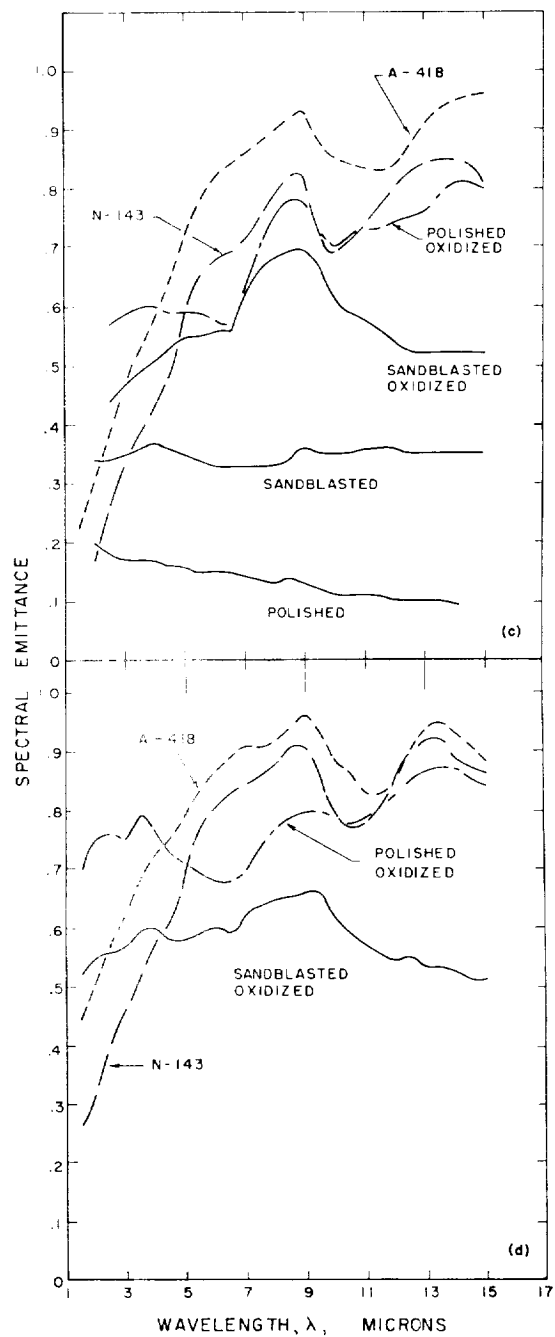
(c) Inconel; 900° F.

(d) Inconel; 1,800° F.

Figure 6.- Concluded.
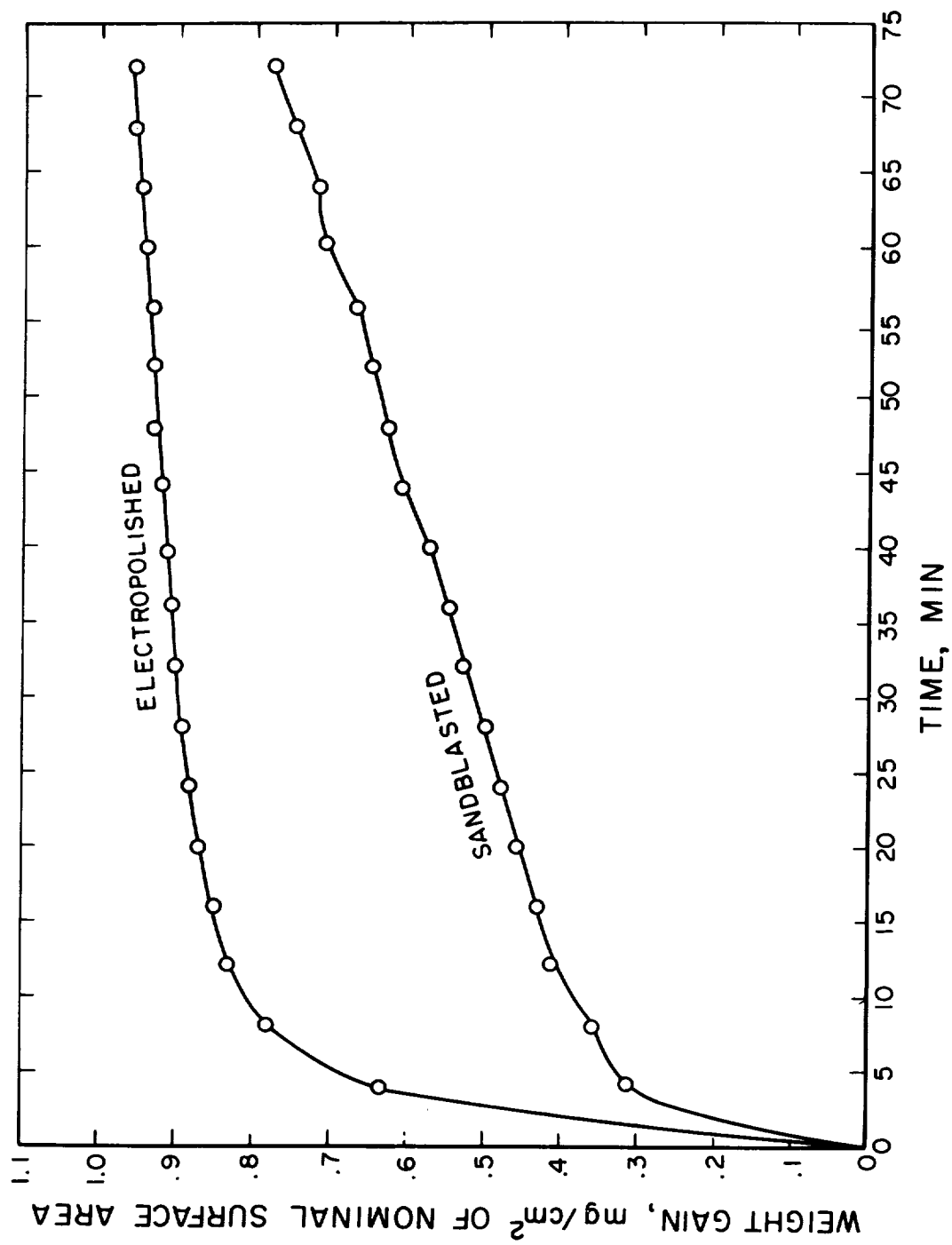
Figure 7.- Weight gain in air at 1,800° F for electropolished and sandblasted specimens of Inconel plotted as a funtion of time.

WAVELENGTH, MICRONS

2.0 MILS ON INCONEL

4.8 MILS ON INCONEL

5.8 MILS ON INCONEL

2.2 MILS ON STAINLESS STEEL

5.5 MILS ON STAINLESS STEEL

(a)
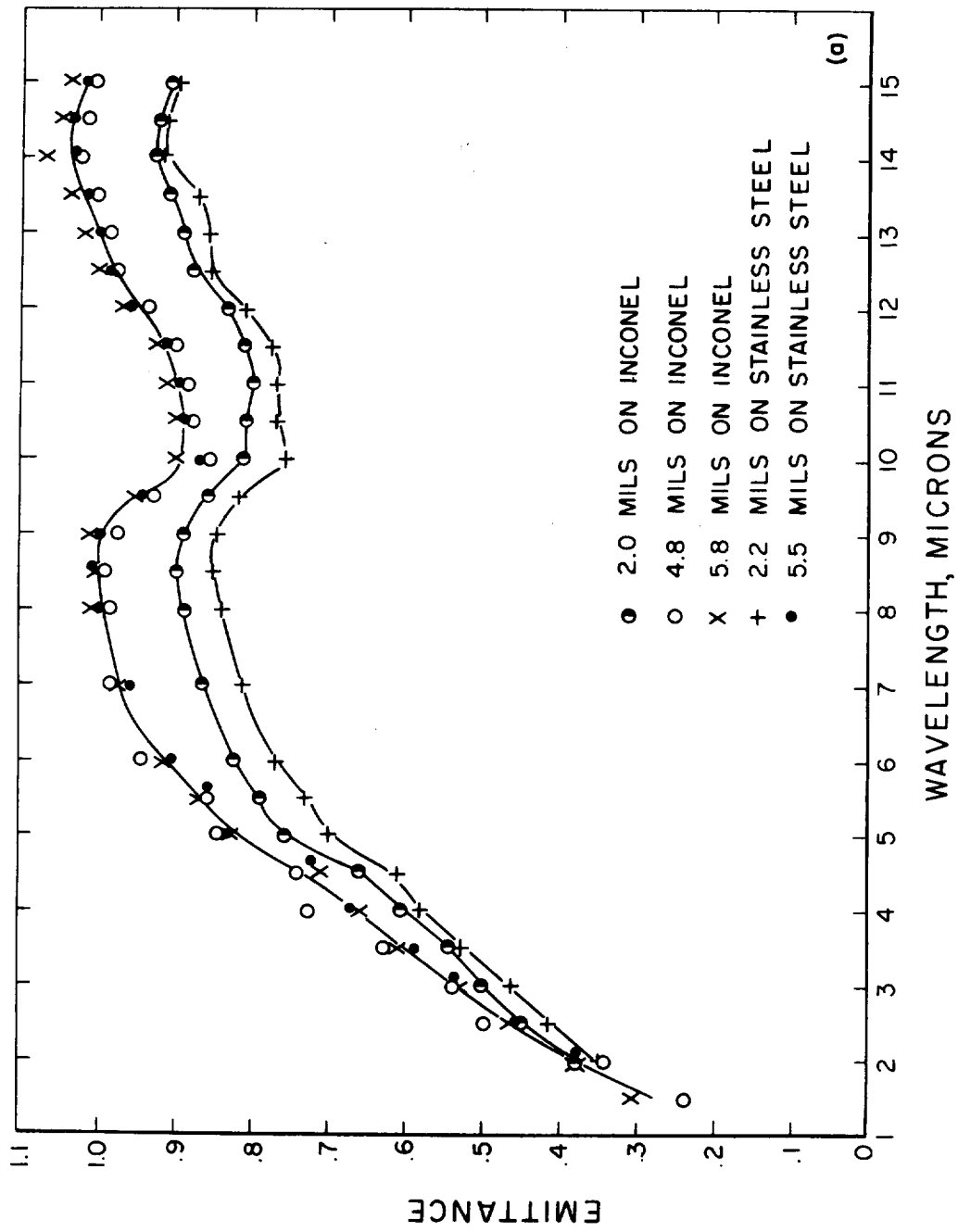
(a) Coating A-418 at 1,200° F.

Figure 8.- Spectral-emittance curves for metal specimens with coatings of different thicknesses.

WAVELENGTH, MICRONS

	2.6 MILS ON INCONEL
○	4.9 MILS ON INCONEL
×	8.6 MILS ON INCONEL
+	2.2 MILS ON STAINLESS STEEL
●	5.1 MILS ON STAINLESS STEEL
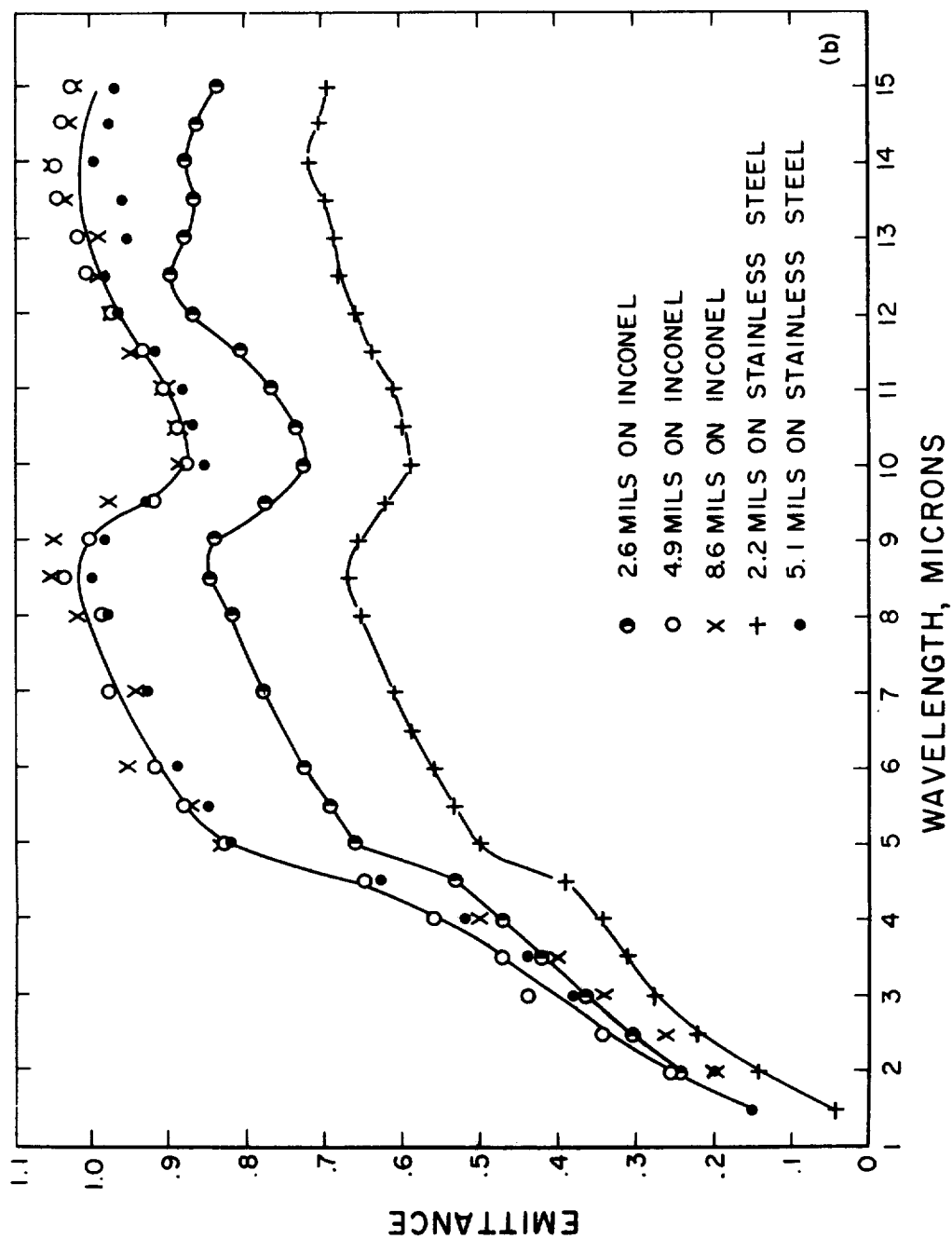
(b) Coating N-143 at 1,200° F.

Figure 8.- Concluded.

1. Materials, Properties -
   Thermal   (5.2.11)
I. Richmond, Joseph C.
II. Stewart, James E.
III. NASA MEMO 4-9-59W
IV. National Bureau of
    Standards

NASA

NASA MEMO 4-9-59W
National Aeronautics and Space Administration.
SPECTRAL EMITTANCE OF UNCOATED AND
CERAMIC-COATED INCONEL AND TYPE 321
STAINLESS STEEL. Joseph C. Richmond and
James E. Stewart, National Bureau of Standards.
April 1959. 30p. diagrs., tabs.
(NASA MEMORANDUM 4-9-59W)

The normal spectral emittance of Inconel and type 321 steel with different surface treatments was measured at temperatures of 900°, 1,200°, 1,500°, and 1,800° F over a wavelength range of 1.5 to 15 microns. The measurements involved comparison of the radiant energy emitted by the heated specimen with that emitted by a comparison standard at the same temperature. Surface treatments included electropolishing, sandblasting, electropolishing followed by oxidation, sandblasting followed by oxidation, application of NBS coating A-418, and application of NBS ceramic coating N-143.

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